BENCHMARKING OF CLEANER PRODUCTION IN SAND MOULD CASTING COMPANIES

Purpose: The purpose of this research was to develop new sustainability indicators consistent with the sand mould casting industry, through Benchmarking of Cleaner Production (CP), in order to identify the levels of practice and performance of companies of the casting sector. In addition, a lean manufacturing checklist was specified in order to verify the presence of lean manufacturing techniques employed to eliminate waste towards CP. No previous work was found in the literature that attempts to assess practices and performance of companies performing sand mould casting (a significantly polluting manufacturing process) in the context of cleaner production and lean manufacturing.

Methodology: For the application of this benchmarking, nine companies from the sand mould casting sector were studied, where the profile of each company was analysed through 8 variables and 47 indicators. Data were obtained through face-to-face visits and questionnaire application in the companies, and the data were analysed both quantitatively and qualitatively.

Findings: The results obtained were the diagnosis of companies' practices and performance resulting from their position in the benchmarking charts, as well as the identification of the areas in which companies should implement improvements aiming at achieving CP.

Research limitations: This research was developed specifically for sand mould casting companies, and each process has its own characteristics.

Practical limitations: 14 companies that perform sand mould casting were invited to participate in this survey, but unfortunately five companies declined to participate.

Value: It is important to diagnose casting companies regarding cleaner production practices, performance and deployment potential. Thus, important negative issues in the company can be identified and, with this information, they can develop actions focused on cases that need more attention. In addition, this work contributes to evaluate the relationship and efficiency of improvement actions developed by companies in the context of both lean manufacturing and cleaner production, aiming to reduce or eliminate the environmental impact. The improvement of practices and performance of a company regarding cleaner production is considered to be beneficial to supply chain management in the context of sustainability, as the other participating companies are likely to seek ways to reduce environmental impact, and the diagnostics provided by this work may also be used by those companies.

Keywords: Cleaner Production, Casting, Lean Manufacturing, Benchmarking, Sustainable Manufacturing, Supply Chain Management.

1. Introduction

Adopting sustainability has become an essential aspect over the last decade for industries to endure in the global market (Yadav et al., 2020). Mangla et al. (2014) point out that the increasing environmental awareness force the introduction of new laws and policies, which drives business decisions in a competitive world that effectively takes the environment into account. However, industry consumes a large amount of natural resources (Roberts, 2004; Sikdar, 2003). Product manufacturing consumes high levels of energy, from raw material extraction, manufacturing, transportation, use and disposal (Li et al., 2013). The control of production activity has been increasingly restrictive in the aspects related to emissions, effluents and waste generated by manufacturing processes (Monte et al., 2009; Fatta et al., 2004). Therefore, further studies related to sustainable manufacturing are extremely important for companies to be able to develop practices that are beneficial to the planet.

Like other manufacturing processes, casting makes part of a sequence of processes/steps that compose a supply chain (Tan et al., 2005), and each of these steps normally has some impact on the environment. In this context, it is important to use means to assess whether casting companies take into account aspects related to the environment in their processes. This assessment contributes to facilitating green procurement, which addresses issues such as waste management, energy management, and packaging, resulting in high efficiency and low pollution levels (Rane and Thakker, 2019). Procurement in an Industry 4.0 context was evaluated by Bag et al. (2020), who mentioned that procurement plays an important role in circular economy operations (Jakkar et al., 2019).

The casting process consumes a large part of natural resources (Dalquist and Gutowski, 2004). All excess material that does not return to the process is largely discarded into the environment (Inderfurth, 2005). Also, the lack of use of these discarded materials contributes to the degradation of the environment. In this scenario, there are some alternatives to minimize this problem, such as modifying product design using new materials (Simon, 2019; Davies, 2016; Hanssen, 1995), or applying procedures that minimize pollution and waste (Sharma et al., 2019; Misra and Pandey, 2005).

In order to avoid damage to the environment, repair costs, and legal implications, it is important that smelters (as well as professionals in other fields) identify sources of pollutant emissions in their industrial facilities and be aware of the degree of risk to the environment, so as to choose the most appropriate and efficient form of control (LaGrega et al., 2010).

Within the scope of sustainability practices applied to companies, Cleaner Production (CP) is highlighted (Gale, 2006; Fresner, 1998). CP seeks to provide preventive actions in order to minimize the impact on the environment as well as prevent actions are taken only at the output of the production system (Ramos et al., 2018), which are referred to as "end-of-pipe" solutions (e.g. incineration and landfilling) (Gehin et al., 2008).

Given this scenario, this research proposes sustainability indicators consistent with the sand mould casting industry, through Benchmarking of Cleaner Production (CP), in order to identify the levels of practice and performance of companies of the casting sector. In addition, a lean manufacturing checklist was specified in order to verify the presence of lean manufacturing techniques employed to eliminate waste towards CP. There is a lack of evidence in the literature that attempts to assess practices and performance of companies performing sand mould casting (a significantly polluting manufacturing process) in the context of cleaner production and lean manufacturing.

2. Previous Related Works

2.1. Casting Process

Casting is a manufacturing process in which iron, steel or non-ferrous metals (e.g. aluminium, copper) melt, and solidify into moulds, so that the shape of the mould cavity determines the shape of the object (Benhabib, 2003). There are different types of casting processes, and the most used is the sand process. It uses disposable moulds made of a mixture of casting sand with a binder, resulting in moulds with significant strength and structure (Groover, 2010). There are several types of sand that can be used, including: silicon oxide, chromite, and zirconium silicate (Black and Kohser, 2017). Sand is very important to obtain a quality melt, since this is where the moulds, cores and channels are made. As such, sands require various properties to improve product quality, including: refractoriness, permeability, flowability, and chemical inertness (Kumaravadivel and Natarajan, 2013; Beeley, 2001).

By obtaining the molten material and having the core and moulds ready and assembled, the pouring process begins, in which the liquid metal is transferred from the furnace to the pouring pan, which will pour the metal into the mould. The main variables in this phase are the temperature and the speed of pouring, as too high a speed may result in erosion of the sand and inclusion of grains in the part. After the required cooling time the part is demolded, where a significant part of the removed sand is sent for regeneration and reuse, while the cooled and mould-free part is sent to the next casting step, which corresponds to finishing processes such as blasting and machining (Black and Kohser, 2017; Benhabib, 2003).

Metal casting is considered a polluting activity due to the transformation of the inputs involved in the process, resulting in the formation of solid waste and atmospheric pollutants (Dalquist and Gutowski, 2004).

Although it is possible to reuse a very large amount of the used sand, there is a limited amount of cases in which these sands can be effectively reinserted into the process (Siddique and Noumowe, 2008). This is because the sand particles, after being used in the cycles of the casting process, lose the angular shape necessary for the formation of moulds with adequate strength and permeability, in which case the sand becomes a residue (Joseph et al., 2017). Therefore, casting sand is considered one of the main environmental problems in the sector (Romeiro et al., 2013).

2.2. Casting Industry

Casting is considered one of the main sectors that influence the world economy. Since 2010, the sector's operating capacity exceeds 91 million tons per year. The last decade has brought significant changes to the map of the world's largest casting producers (Holtzer et al., 2014). In 2010 the world's production of 88% of castings was concentrated in 10 countries and, in that same year, Brazil had 42% increase in its casting production. The ten largest casting producers, by country, are shown in Table 1.

Table 1. Ten largest casting producers, by country (adapted from Statista, 2017)

	Country	Production (million metric tons)
1	China	49.40
2	India	12.06
3	USA	9.67
4	Germany	5.48
5	Japan	5.45
6	Russia	4.22
7	Mexico	2.91
8	Korea	2.60
9	Italy	2.24
10	Brazil	2.22

The number of casting plants in the world is around 48,000, of which 55% are located in China. Second in terms of number of casting plants is India (9%). Most of these plants produce cast iron parts, and 80% of these companies employ less than 250 people per plant (Holtzer et al., 2014).

World's casting production reached 109.8 million tons, an increase of 5.3% when compared to the previous year (Modern Casting, 2017). China has experienced rapid growth in recent years, having an extremely competitive market, capable of producing on a global scale at reduced cost and with rising technological standards (Holtzer et al., 2014).

2.3. Cleaner Production (CP)

Cleaner Production (CP) is the application of a technical, economic and environmental strategy integrated to processes and products in order to increase the efficiency in the use of raw materials, water and energy by preventing, minimizing or recycling waste and emissions, with environmental, economic and occupational health benefits (UNEP, 2006; Nobrega et al., 2019).

According to UNEP/UNIDO (2012), CP can be defined as a preventive environmental strategy applied continuously and integrated to products, processes and services to increase eco-efficiency and reduce risks to humans and the environment. CP takes into account environmental variables at all levels of a company, such as raw material purchasing, product engineering, after sales, and compares the company's economic results along with environmental factors (Montalvo, 2008).

By implementing CP, the company will have the means to contribute to a better knowledge of its production process, due to continuous monitoring to maintain and develop an eco-efficient production system. According to De Oliveira (2013), the integration of Quality System, Environmental Management and Occupational Safety and Health is important in the context of Cleaner Production. Many economic and environmental advantages resulting from CP can be cited (Nobrega et al., 2019):

- Lower consumption of raw materials and inputs, contributing to the conservation of natural resources;
- Lower volume and weight to be treated at water and wastewater plants, eliminating the need for investment to expand their operating capacities;
- Fewer materials to be disposed of in landfills, increasing their useful life;
- Fewer accidents, achieving better employee health, occupational safety and morale, resulting from improvements in the work environment;
- Agility to comply with environmental legislation.

2.4. Environmental Assessment of Manufacturing Companies

Mangla et al. (2013) proposed a model to identify and analyse key decision variables in order for a company to initiate product recovery and improve overall performance. A case study was conducted in the paper industry. They concluded that variables such as environmental issue, cost, regulations and supplier commitment have higher driving impact power than variables such as productivity and effectiveness, and capacity utilisation. According to Tseng et al. (2014), companies must constantly improve their manufacturing processes whilst facing challenges as to how they could manage eco-efficiency in its operations, in a context of green market competition. They considered some criteria for assessing eco-efficiency in green supply chain practices, which include: reduce the use of fresh water and increase recyclability, reduce dispersion of toxic and hazardous materials, and reduce energy intensity of goods or services. Mangla et al. (2015) analysed the risks for effective implementation of green supply chain practices. They applied the method to four Indian manufacturing companies, and they applied fuzzy Analytical Hierarchy Process (AHP) (Van Laarhoven and Pedrycz, 1983) in the analysis. Six categories of risks and twenty-five specific risks were identified, and they concluded that the operational category risks (e.g. machine, equipment or facility failure) are the most important.

More recently, Gandhi et al. (2016) evaluated success factors associated with green supply chain management in Indian manufacturing companies. The evaluation was performed using a method that combines AHP (Saaty, 2000) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) (Gabus and Fontela, 1972) approaches. They inferred that the global competition main factor (e.g. competitiveness) has a very high influence in increasing green supply chain effectiveness. The relative importance order of the remaining main factors is: organisational factor (e.g. employees involvement), government factor (e.g. waste disposal norms), financial factors (e.g. implementation of reverse logistics), and external factors (e.g. information technology). Whereas Pati et al. (2016) proposed a model with performance indicators to assess the environmental performance of a supply chain. The model was applied in a company of the automotive sector, providing means to benchmark the company's first tier suppliers. For instance, a project may be more energy efficient, but worse with respect to dangerous waste generation.

Song and Wang (2017) studied the incentive effects of Chinese companies' participation in the global value chain regarding their green technologies. Factors considered in their analysis include enterprise scale, corporate ownership, and research and development investment. They concluded that the higher the participation degree in the global value chain, the stronger the effects on green technology improvement, except state-owned ones. Also, larger enterprise scale and improved production efficiency are beneficial to green technology progress. In another study Mangla et al. (2018) distinguished 16 barriers to adopting circular supply chain management (CSCM) concepts by taking an Indian perspective. The barriers "lack of environmental laws and regulations" and "lack of preferential tax policies for promoting the circular models" have higher effectiveness in CSCM implementation. Thakur and Mangla (2019) carried out a study to extend the change management initiatives to operations and supply management practices in five home appliances companies in India. They identified 28 key factors (e.g. green procurement, green manufacturing, waste management, community wellbeing and safety) under eight dimensions to sustainable operations management based on human-operational-technological aspects. They inferred that Environmental aspects, Innovation and technological aspects, and Resources recovery management dimensions should be prioritized. Choudhary and Sangwan (2019) compared the reasons for green supply chain management implementation, levels of implementation and improvement in performance in four Indian ceramic companies. They concluded that internal environmental management is the motivating power behind the implementation of other green supply chain management practices, driving the environmental and operational performance. Also, the impact of the pressures to adopt green supply chain management practices is high on Indian ceramic companies, but the implementation of practices is in the early stage.

These publications provided significant contributions to individual organizations and supply chains that are willing to develop activities that are beneficial to the environment. However, none of those works attempted to assess the practices and performance of manufacturing companies in the context of cleaner production and lean manufacturing using benchmarking. Also, those works did not evaluate the casting process. Khoo et al. (2001) presented a case study of a supply chain encompassing the distribution of aluminium metal, from a metal supplier to a casting plant, then the billets from the casting plant to the component producer, and finally, die-cast components from the component producer to the market (i.e. four plants). The generated green supply chain takes into account transport pollution, marketing costs, time to market, recycling of scrap metal and energy conservation. Simulation was used to select distances and transportation, allowing testing decisions and their outcomes. Their work did not perform assessment of practices and performance of the companies.

Tan et al. (2005) used Life Cycle Assessment (LCA) (Assies, 1992) to study the final aluminium cast product in a supply chain composed by a refinery, a smelter, and a casting plant. Different scenarios were considered for improving the environmental performance of the system. Some of the results by Tan et al. (2005) included a reduction in scrap metal, reject rates and red mud, and increased energy efficiency. Although their work contributed to improving the practices of the studied companies in the aluminium supply chain, they did not consider variables such as people, information and product development, nor lean manufacturing aspects.

2.5. Lean Manufacturing and Cleaner Production

Bergmiller and McCright (2009) developed a study to verify the correlation between LM and CP. They identified that when CP is applied together with LM, Cleaner Production boosted Lean Manufacturing, especially with respect to production costs. CP and LM have similar points for deployment in an organization and, together, can be complementary tools as they combine systemic elements with waste reduction goals (Ramos et al., 2018). LM and CP have common goals, and this becomes a great potential for Lean Manufacturing and Cleaner Production to be applied together (Bergmiller, 2006). According to Bergmiller (2006):

- Lean Manufacturing infrastructure serves as a catalyst for achieving Cleaner Production results. Therefore, companies that apply LM comprehensively have better CP results, thus allowing identifying the synergy between the two systems;
- CP leads to similar results for LM, in particular cost savings;
- Companies applying LM in all plant functions favour waste elimination and contribute to CP practices.

For Kuriger et al. (2011), in order to successfully combine LM and CP, it is important to work with appropriate indicators to assess and monitor production, being very important to combine productivity and sustainability metrics. According to Bergmiller (2006), there is a significant reduction in energy consumption in companies that adopt LM due to the reduction of waste such as unnecessary processes and transportation.

Given the above scenario, the next section presents the application of the method of Benchmarking of Cleaner Production to sand casting companies, in order to assess their practices and performance with regard to cleaner production and lean manufacturing.

3. Method of Benchmarking of Cleaner Production

Xerox Corporation started using benchmarking in the late 1970s (Camp, 1995), being very important for performance management and improvement of processes (Manning et al., 2008). Also, benchmarking results in cost reduction in carrying out operations, and supports strategic planning (Kazançoglu et al., 2019).

The CP benchmarking method for sand mould casting companies was developed based on the CP benchmarking concept proposed by Ramos et al. (2018) and Tomelero et al. (2017), following the methodology of Benchmarking Made In Europe (Hanson and Voss, 1995). The method is structured in two stages: (a) interviews conducted in person at the companies; and (b) evaluation of the results. 14 companies were invited to participate in this survey, but five companies declined to participate. In the evaluation stage, the partial indexes of both practices and performance are calculated, according to the result of the scores given by the companies for each of the indicators of the research variables. In order to transform the scores into percentage values, each score is multiplied by 20%.

With these percentages, the practice and performance partial indices are calculated for all variables under analysis, and the general indices are calculated using simple average. For each indicator of the variables, a scoring system ranging from 1 to 5 is adopted. This scoring system comes from the Lean Benchmarking method (Tomelero et al., 2017), and describes three situations for each indicator, as described below:

- Score 1 - Corresponds to a basic level (20%) of practice or performance;
- Score 3 - Corresponds to an intermediate level (60%) of practice or performance;
- Score 5 - Corresponds to excellence (100%) of practice or performance.

Scores 2 (equivalent to 40% practice or performance) and 4 (equivalent to 80% practice or performance) refer to the intermediate values of the indicator, and are selected when the company has some practices or performances in both columns, or is developing the practices of the lower column without, however, having reached the state described in the upper column. Fractional values cannot be used, since integer values should be used in order to facilitate reading the obtained results.

After the score scale from 1 to 5 used in the questionnaire is transformed into percentage, it is then placed on three types of charts for the analysis of results: (a) practice versus performance chart, (b) radar chart, and (c) bar graph.

3.1. Evaluation stage

At this stage, the indicators developed for CP are measured in sand casting companies, which integrate the Benchmarking method proposed in this work. Eight variables (Management, People, Information, Supplier/Organization and Customer, Environmental Profile, Product Development, Process, Energy Profile) are considered, and a questionnaire was applied in order to collect data for obtaining the results. A description of the variables is provided below:

- Management: through this variable it is sought to understand how companies consider the management issue, as well as the division of labour and responsibilities within the organization.
- People: this variable is used to evaluate whether companies actually invest in employees to obtain CP, taking into account the availability of resources and also training to prepare employees.

- Information: this indicator is used to investigate the structuring and availability of CP information for the entire company, considering the importance of information for incentive and to help map the critical points that need more attention.
- Supplier/Organization and Customer: this indicator is used to assess if there is a relationship between supplier, organization and customer in the product and process development process in order to favour CP.
- Environment: this indicator is used to analyse data related to technological innovations of product and process in the surveyed companies; the techniques and solutions adopted to eliminate or minimize environmental impacts; the factors that contributed to the investment in environmental management; the standards used; the use of production inputs and the control and destination of process extras.
- Product Development: it is used to investigate how the company is working towards CP in the developed products.
- Process: this variable is used to analyse how the company is working toward achieving CP in production.
- Energy Profile: through this variable aspect related to technological innovation are analysed, which contributes to the reduction of energy and fuel consumption. This variable is used to identify the practices adopted by the companies regarding energy consumption, and provides information on the acquisition or use of machinery, equipment and resources employed in the casting companies seeking to reduce energy consumption, as well as the management of these inputs.

The completion of the proposed questionnaire, whose indicators are presented in Tables 2 to 9, was performed through face-to-face visits, as well as visual analysis of aspects related to the investigated variables. The scores assigned to each indicator were presented to the company representative, so that he/she could verify if the score was appropriate in the company context. In order to fill in the indicators it was necessary to know the procedures of the companies, as well as improvements and work developed and under development. In assigning the scores, the current situation of the company was considered as well as plans or projects in progress and pilot projects.

Table 2. Indicators of the Management variable

Indicators of Management		
Practices	**Description**	**Score**
M-01	There are Cleaner Production policies within the company, especially in the sand casting industry.	

M-02	Management is committed to Cleaner Production deployment processes.	
M-03	There is some kind of incentive from management to implement and progress Cleaner Production.	
M-04	There are employees from every part of the sand casting process involved in Cleaner Production.	
Performances	**Description**	**Score**
M-05	There are performance indicators related to Cleaner Production in the sector.	
M-06	There are CP development action plans.	
M-07	Employee availability for CP deployment and progress in the sector.	

Additional information about the practice and performance indicators of the management variable is given below:

- M-01: This indicator enables verifying whether companies adopt any practice related to CP, conveying the necessary knowledge to their employees, suppliers and customers regarding CP policies and actions of the company.
- M-02: This indicator shows the degree of commitment of the highest level of the company to CP, that is, if in fact there is any incentive favouring CP practices in sand mould casting in order to apply preventive actions.
- M-03: This indicator shows how much company management values and recognizes the performance achieved by employees regarding the implementation of CP, considering the importance that incentives provide for new achievements. It is also observed the investment, incentives and management recognition for the entire structure of sand mould casting in relation to CP.
- M-04: This indicator assesses whether sand mould casting employees are involved in CP actions, considering, for example, shop floor, engineering, supply employees, etc.
- M-05: This indicator is used to assess whether the company has any information structure that is intended for CP in order to comply with the company's policy regarding the preventive actions carried out, and whether such structure is actually used by management to monitor the improvements implemented.
- M-06: This indicator is used to assess whether the company prepares and structures action plans for the development of CP, and whether such plans are actually applied. This indicator is also used to assess management-related practice indicators.
- M-07: This indicator assesses the availability of employees in sand mould casting who dedicate part of their time to develop activities aimed at CP.

Table 3. Indicators of the People variable

Indicators of People		
Practices	**Description**	**Score**
P-01	There is structure and ease for employee training.	
P-02	There are training programs based on CP concepts and techniques for the sand casting industry.	
Performances	**Description**	**Score**
P-03	There are trained collaborators to apply and disseminate their CP concepts to their peers.	
P-04	Availability of resources needed for employees so that the application of CP actions is consistent in the sand mould casting industry.	

Additional information about the practice and performance indicators of the people variable is given below:

- P-01: This indicator evaluates the structure that the company provides so that employee training can be carried out.
- P-02: This indicator is used to assess the availability of training for teams focused on CP techniques, where the importance of this practice for the company is clarified, especially the environment, and what are the steps adopted by the company regarding preventive actions with the objective of reaching cleaner production.
- P-03: This indicator is used to evaluate if employees, especially those destined to carry out preventive actions, are trained or are being trained with regard to CP actions in order to understand their importance and also act to improve the sector.
- P-04: It is observed through this indicator the investments of management to carry out improvements in products and production processes in order to obtain CP. By making resources available for preventive actions, the company encourages the employees to improve CP.

Table 4. Indicators of the Information variable

Indicators of Information		
Practices	**Description**	**Score**
I-01	CP information is available to all casting company employees.	
I-02	There is information on financial indicators to report progress related to CP.	
Performances	**Description**	**Score**
I-03	CP casting foundry information is updated frequently.	

I-04	There was a reduction in expenses and costs with the adoption of CP.	
I-05	There is dissemination of the results obtained with CP.	

Additional information about the practice and performance indicators of the information variable is given below:

- I-01: This indicator seeks to assess the ease and availability of information accessible to employees about CP and its practices in sand mould casting.
- I-02: Through this indicator the company's ability to measure the advances provided by CP through financial indicators is verified, considering the importance of verifying the financial impacts in addition to measuring the return for the company resulting from the application of preventive actions.
- I-03: This indicator analyses the frequency with which CP information is updated, in addition to verifying the practices adopted.
- I-04: This indicator is used to assess whether the financial indicators actually show results and whether they are structured to the point of enabling measuring the progress made with CP.
- I-05: This indicator is used to assess whether the company discloses the results obtained through the actions of CP, thus obtaining the decentralization of data and easy access to them.

Table 5. Indicators of the Supplier, Organization and Customer variable

Indicators of Supplier, Organization and Customer		
Practices	**Description**	**Score**
SOC-01	Customer and supplier participation in the concept, product and process development.	
SOC-02	Suppliers and customers participate in ongoing product and process development reviews.	
SOC-03	Incentives to suppliers and customers to achieve cleaner production.	
Performances	**Description**	**Score**
SOC-04	Projects involving suppliers/customers in product development and cleaner processes.	
SOC-05	Compliance with customers' requirement for environmental impact prevention.	

Additional information about the practice and performance indicators of the supplier, organization and customer variable is given below:

- SOC-01: This indicator is used to verify with the company whether suppliers and customers participate in the process of developing new products and processes in sand mould casting.

- SOC-02: This indicator assesses whether the participation of suppliers and customers is continuous in the process of improving products and processes, considering both new products and processes and the improvement of existing ones.
- SOC-03: This indicator analyses whether the company encourages customers and suppliers to purchase products and processes that have less impact on the environment, thus favouring CP.
- SOC-04: This indicator enables evaluating, through projects, the frequency of participation of customers and suppliers in the development of products and processes with less environmental impact.
- SOC-05: This indicator is used to verify whether the company is meeting the requirements of customers in order to develop products and processes through the application of preventive actions that are cleaner.

Table 6. Indicators of the Environment variable

Indicators of Environment		
Practices	**Description**	**Score**
E-01	The company makes use of solid waste incinerator.	
E-02	Discarded slag from the casting process is used sustainably.	
E-03	The company has some equipment for controlling and monitoring particulate matter.	
E-04	There is equipment that performs the control of the emission of gases.	
E-05	The company adopts a process aimed at reducing water consumption.	
Performances	**Description**	**Score**
E-06	There was reduction of both solid waste and the levels of atmospheric pollutants released by the casting process.	
E-07	The company was able to reduce water consumption by adopting some reuse or other process.	

Additional information about the practice and performance indicators of the environment variable is given below:

- E-01: This indicator assesses whether the company has among its practices the use of solid waste incinerators, since it is capable of reducing up to 90% the amount of solid waste in landfills, in addition to preventing accidental or intentional disposal. The incinerator also eliminates substances considered hazardous, in addition to enabling converting electrical energy through the heat energy generated by the incinerator.
- E-02: This indicator assesses whether the company reuses the slag generated by the process in other processes.

- E-03: Through this indicator it is assessed whether the company adopts practices related to the control of particulate materials, which ends up reducing significantly the emission of pollutants in the atmosphere, in addition to generating dry residue, reducing the costs with the post-treatment of particulates. This indicator also assesses whether the company monitors the levels of atmospheric pollution generated.
- E-04: It is assessed whether the company has equipment that controls gas emissions, since the gases released into the atmosphere cause the ozone layer to decrease, contributing to global warming, in addition to other climatic events that unbalance the environment.
- E-05: This indicator shows the company's commitment to reducing water consumption in its process, with actions that seek to contribute to the conscious use of this important natural resource.
- E-06: With this indicator it is verified if there was a reduction in the levels of atmospheric pollution, as well as making it possible to evaluate the performance of the practices established in indicators E-01, E-03 and E-04.
- E-07: It is assessed whether the company was successful in reducing water consumption, reusing water in other sand mould casting processes, or even in other sectors of the company.

Table 7. Indicators of the Product Development variable

Indicators of Product Development		
Practices	**Description**	**Score**
PD-01	The product is designed from the principles of lifecycle management.	
PD-02	A material that can cause environmental problems is replaced with another that does not cause damage to the environment.	
PD-03	There are studies focused on the development of components to be recycled, and even reused in other products of the company.	
Performances	**Description**	**Score**
PD-04	Reduction in the amount of material that causes damage to the environment.	
PD-05	Recycled material or component is used.	
PD-06	Product useful life expansion.	

Additional information about the practice and performance indicators of the product development variable is given below:

- PD-01: This indicator assesses whether sand mould casting applies the concepts of life cycle assessment for new products under development and also for the improvement of existing products.

- PD-02: This indicator is used to verify whether the company seeks alternative materials for the development of products in order to minimize damage to the environment, in addition to favouring the recycling process.
- PD-03: With this indicator it is assessed whether the company develops components in order to contribute to its recycling at the end of its life cycle.
- PD-04: Through this indicator it is assessed whether the company, by adopting alternatives aimed at reducing the amount of harmful material, managed to reduce the amount of use of the material. This indicator also measures the performance of the PD-02 indicator.
- PD-05: This indicator assesses how much the company, through the alternatives of material use, favoured the reduction of residues in sand mould casting.
- PD-06: This indicator assesses whether the company has achieved an increase in the product's useful life.

Table 8. Indicators of the Process variable

Indicators of Process		
Practices	**Description**	**Score**
PR-01	The company reuses sand used in the sand mould casting process.	
PR-02	The company adopts appropriate LM aspects for sand mould casting in order to reduce environmental impact.	
PR-03	Process-generated residues are separated before being recycled, reused or disposed of.	
PR-04	The company conducts evaluation and control seeking the reduction of solid residues and toxic materials.	
PR-05	Unused sand is disposed of in landfills.	
Performances	**Description**	**Score**
PR-06	There was reduction of solid residues and toxic materials.	
PR-07	Environmental impacts were reduced with the adoption of LM techniques.	

Additional information about the practice and performance indicators of the process variable is given below:

- PR-01: It is evaluated using this indicator whether the company reuses the sand used in the sand mould casting process, since sand is considered a major environmental problem.
- PR-02: This indicator assesses whether the company adopts Lean Manufacturing techniques so that it can favour CP actions.
- PR-03: This indicator seeks to assess whether the company adopts actions aimed at separating residues properly during the process, thus enabling giving an appropriate destination for residues.

- PR-04: This indicator assesses the company's concern with the generation of solid residues and toxic materials, in addition to verifying whether the company seeks alternatives to reduce these residues and materials.
- PR-05: This indicator assesses whether the company has the practice of disposing of unused sand in an appropriate place.
- PR-06: This indicator is used to evaluate if the company reuses as much of the sand used in the process as possible. It is known that it is possible to recycle 90% of the sand used in sand mould casting in later processes. This indicator also assesses the performance of the PR-01 practice.
- PR-07: This indicator is used to assess whether the company has achieved results with PR-02, PR-03 and PR-04 practices, reducing the amounts of solid residues and toxic materials generated by the process. in addition to investigating whether the company attained results with the application of LM techniques.

Table 9. Indicators of the Energy variable

Indicators of Energy		
Practices	**Description**	**Score**
EN-01	The company develops new or improved casting process that contributes to reducing energy consumption.	
EN-02	The company implemented a product that demanded less energy in its manufacture.	
EN-03	There is control in the use of energy sources (electricity, oil, gas, etc.)	
EN-04	There is accounting of energy use by the company in the casting sector.	
EN-05	The company adopts processes to reduce electricity consumption.	
Performances	**Description**	**Score**
EN-06	There was a reduction in the use of energy sources.	

Additional information about the practice and performance indicators of the energy variable is given below:

- EN-01: Through this indicator it is assessed whether the company implements new processes in sand mould casting in order to contribute to the reduction of energy sources (electricity, oil, gas, etc.).
- EN-02: This indicator is used to assess whether the company manufactures products that use the least amount of energy possible in their production.
- EN-03: This indicator seeks to assess whether there is control of expenses with the use of energy sources, in addition to assessing the use of electricity and also the use of gas in smelting furnaces.

- EN-04: This indicator is used to assess if the company has practices related to the demand for electricity consumed in the production process.
- EN-05: This indicator enables assessing whether the company has reduced the use of energy sources (electricity, oil, gas, etc.), in addition to measuring the performance of the four practice indicators in this variable.
- EN-06: This indicator enables assessing whether the established practices have led to good results.

3.2. *Checklist of Lean Manufacturing*

In order to verify which lean manufacturing practices are being applied in the sand casting industries, a method called LM checklist was applied (Ramos et al., 2018). This method has been revised and adapted to enable its application in casting companies.

In the checklist six scenarios are defined for evaluation: (a) NA: not applicable for indicators that, due to the characteristics of the company, are not being applied; (b) NE: does not exist for indicators that are not being applied, but may be applied depending on the characteristics of the company; (c) VW: very weak application; (d) W: weak application; (e) S: strong application; e (f) VS: very strong application. For each indicator, weights were assigned to the evaluation to obtain the final result, as follows:

- VW: weight 2.5;
- W: weight 5.0;
- S: weight 7.5;
- VS: weight 10.

The variables NA and NE are considered as having zero weight and, therefore, are considered non-existent or not applicable. In order to identify which are the most used and applied practices in the companies studied, Equation (1) was used, where variable *n* corresponds to the number of applications referring to VS, S, W and VW.

$$SCORE = \frac{10.0 * \sum VS + 7.5 * \sum S + 5.0 * \sum W + 2.5 * \sum VW}{\sum VS + \sum S + \sum W + \sum VW + \sum NA} \quad (1)$$

This checklist was completed during conversation with the company collaborator and by observing the production system.

3.3. *Characterization of the companies*

Nine companies participated in the survey, and most of them manufacture parts for the automotive sector. There were also companies with a production mix of compressor parts, as well as the production of parabolic and coil springs.

Of the participating companies, 60% were large-sized and 40% medium-sized. Table 10 classifies each participating company according to its size. In this paper companies will be called E01, E02, E03, E04, E05, E06, E07, E08 and E09.

Table 10. Companies studies and their respective size

Company	Size
E01	Medium
E02	Large
E03	Large
E04	Large
E05	Medium
E06	Medium
E07	Large
E08	Large
E09	Medium

4. Results and Discussion

With data from the nine participating companies, the proposed questionnaire was applied in the context of the CP Benchmarking method. Practice and performance analyses were performed for each of the following variables: management, people, information, supplier/organization and customer, environment, product development, process and energy.

The chart of practices and performance is shown in Figure 1. The practice versus performance chart is divided into four quadrants, and for both the horizontal and vertical axes 60% is used to separate the quadrants. The quadrants are classified as: I (high practice and high performance), II (high practice and low performance), III (low practice and high performance) and IV (low practice and low performance).

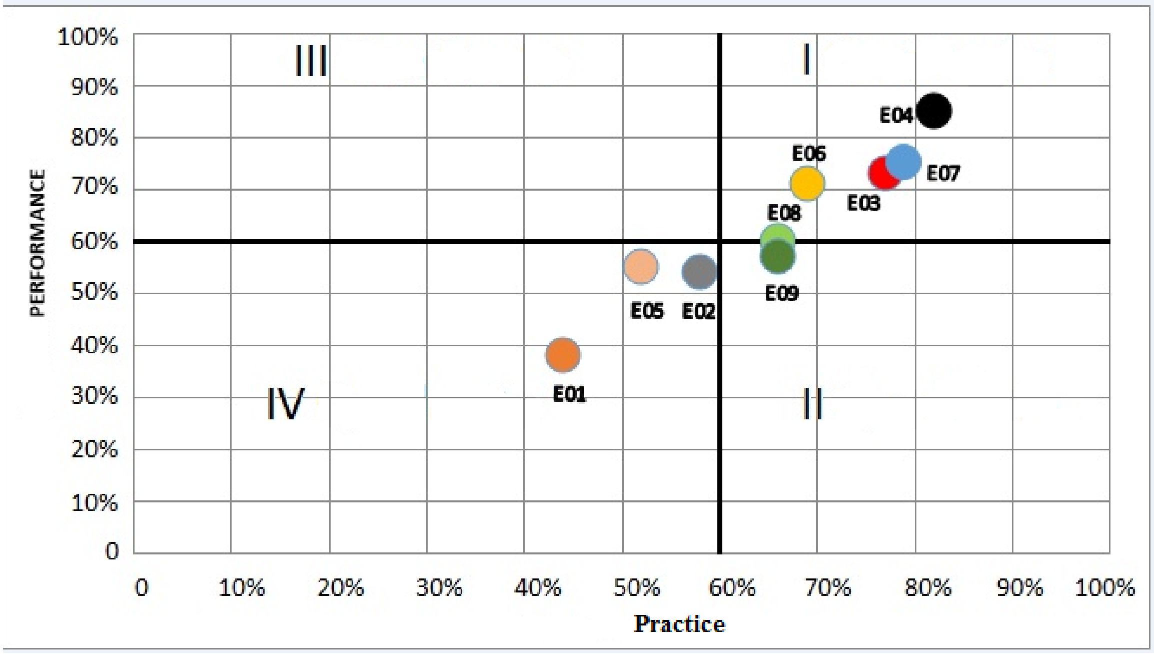

Figure 1. General chart of Practices X Performance

In this survey the overall average of the companies presented 66% in practice and 63% performance. The company with the best performance was E04, a large company, while company E01 had the worst performance among the companies studied, being the newest company in the market, which may explain its low performance. It should be pointed out that only one midsize company was positioned in the first quadrant (company E06), which is in the process of applying lean manufacturing techniques throughout its plant. Table 11 shows the percentage values of practice and performance of the companies studied.

Table 11. Values of practices and performance of the studied companies

Company	Practice	Performance
E01	44%	38%
E02	58%	54%
E03	77%	73%
E04	82%	85%
E05	52%	55%
E06	69%	71%
E07	79%	75%
E08	66%	60%
E09	66%	57%
Average	66%	63%

Company E04 is considered world class because the achieved values of practices and performance show it implements the best actions related to CP, which makes it highly competitive in the international market. Companies E07, E03 and E06 are considered contenders (Hanson and Voss, 1995) as they have invested in CP actions with points to be improved, and are on their way to becoming world class.

The values achieved by companies E08 and E09 position them as promising (Hanson and Voss, 1995), since they have invested in appropriate practices, but need performance improvement. Since companies E02 and E05 have achieved levels of practice between 50% and 60%, they are considered makeweight (Hanson and Voss, 1995) because they have averages below what is considered excellence, but not as low as company E01, which has low levels of both practice and performance.

4.1. Analysis of the radar chart

Through the partial indices of each variable the radar chart is generated for the analysis of the practices and performance of each variable. The radar chart positions the company relative to international industry leaders in each of the areas benchmarked for practice and performance.

In the radar chart there are axes referring to practice and performance, and each axis has a scale from 0% to 100% (Figure 2). The position of each variable is established on this scale by a point, and each point is joined by lines (blue colour) forming a closed polygon. The standard of excellence is achieved by considering 100% of the practice and performance indices. It is considered 60% (red line) as a benchmark of favourable minimum performance that enables the use of tools and concepts of LM in the business setting.

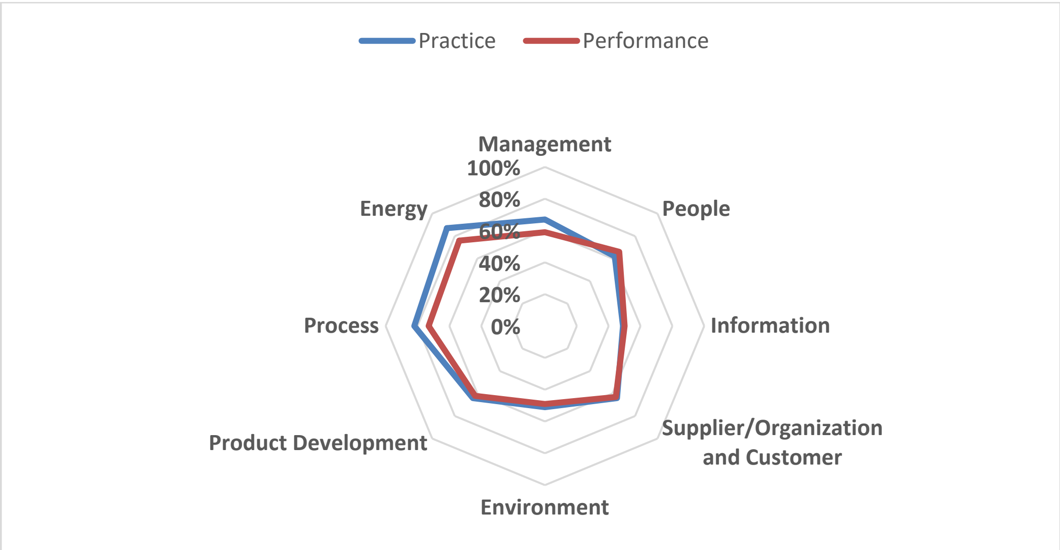

Figure 2. Radar chart of the studies companies

Regarding the radar chart shown in Figure 2, it can be mentioned that some companies have similar levels of practice and performance in many variables, but it is noticed that this fact does not occur in the case of the Process, Energy and Administration variables. The radar chart also allows showing the points that need attention, which are the values in the centre of the chart, allowing studies to perform actions aiming at better results. The points closest to the edges of the graphs indicate better results. Given the data available on the radar chart, it is found that the practice rates are almost equal in five of the eight variables investigated. In general it can be said that the level of practice was higher than the performance, because companies still face some difficulty to consolidate the actions, besides the cultural issue within their organizational structures.

4.2. Analysis of the bar charts

Bar charts are used for causal investigation purposes of the most critical and most positive points of each variable under analysis. Through this chart the practice and performance indicators are presented together, respecting the cause and effect relationship between them. The results of the indicators are shown in the following sections. In the charts, the bars corresponding to Practice indicators are shown in grey, whereas bars referring to Performance indicators are shown in blue.

4.2.1. Analysis of the bar chart based on the Management variable

Observing the chart in Figure 3, the first four indicators evaluate the practices adopted by companies in this variable. For indicator M-01, which assesses the existence of CP policies within the company, it is observed that the companies obtained an average of 58%. With this result, companies still do not have excellence in specific CP policies. However, indicator M-02, which assesses management commitment to CP implementation processes, reached 80%, which shows some responsibility, being an important step towards the implementation of CP (Thakker and Rane, 2018).

An average of 73% was the index obtained for indicator M-03, which assesses whether there is any incentive by management for CP implementation and progress, showing the importance of incentives for new achievements.

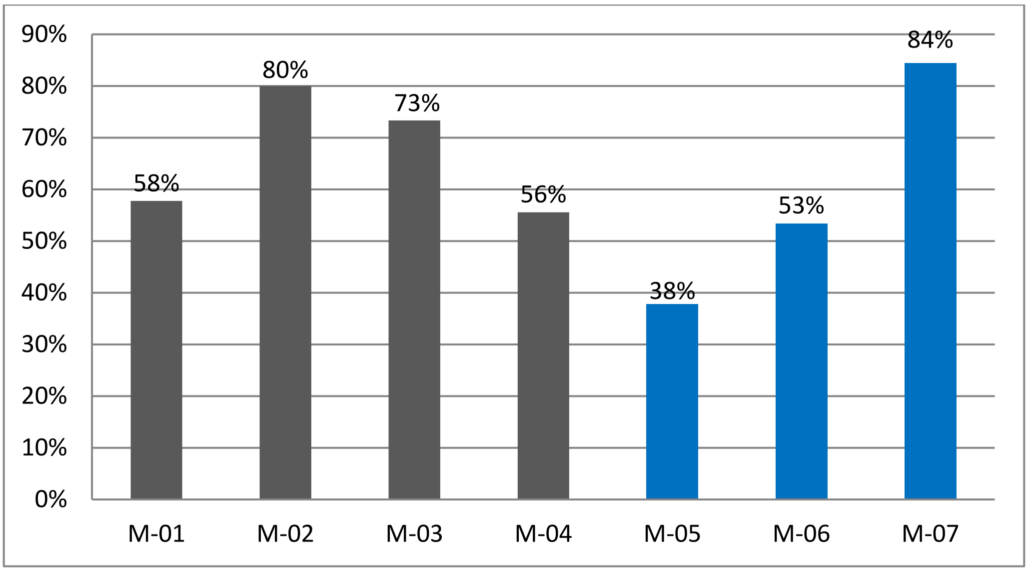

Figure 3. Bar chart with the average of companies for each indicator of the Management variable

PA-04 indicator, which investigates the existence of employees involved and trained in each part of the casting process with knowledge related to CP, had a value of 56%. Many companies mentioned that they need more employees to apply actions related to CP, and this was also the indicator with the worst result in the practices related to the management variable. The low result of this indicator can be interpreted as a great opportunity for actions in order to obtain better results.

In the case of the three performance indicators, PA-05 indicator, which assesses whether the company has any information structure that is intended for CP, had the lowest value of the variable, equal to 38%. It can be inferred that companies still do not provide accurate information on cleaner production, and the availability of such information is important in the context of green supply chain management (Gandhi et al., 2016).

4.2.2. Analysis of the bar chart based on the People variable

In general, the participating companies have a structure for training, as shown in Figure 4. Indicator P-01, which measures the existence of structure and training facility, presented a value of 78%, indicating some ease with respect to training space. Considering the training carried out focused on the concepts and techniques of CP that were evaluated by indicator P-02, it is verified that the companies do not have training programs directed to cleaner production, but for the process seeking to reduce waste. Thus, it is verified for all companies studied that there is a need for the creation and structuring of training that directly addresses CP. Piyathanavong et al. (2019) inferred that lack of training and knowledge is the most significant barrier for the implementation of CP.

The performance indicator P-03, which is directly related to the practice indicator P-02, shows that there is a shortage of employees with the necessary knowledge for CP actions, even though the employees' knowledge is linked with LM, which seeks to reduce waste. Finally, it is noticed that the companies studied have the necessary structures for conducting training. However, these are scarce or non-existent, since employees are usually trained in the employee's integration week and, in this training, the approach is more related to the environment and sustainability than CP.

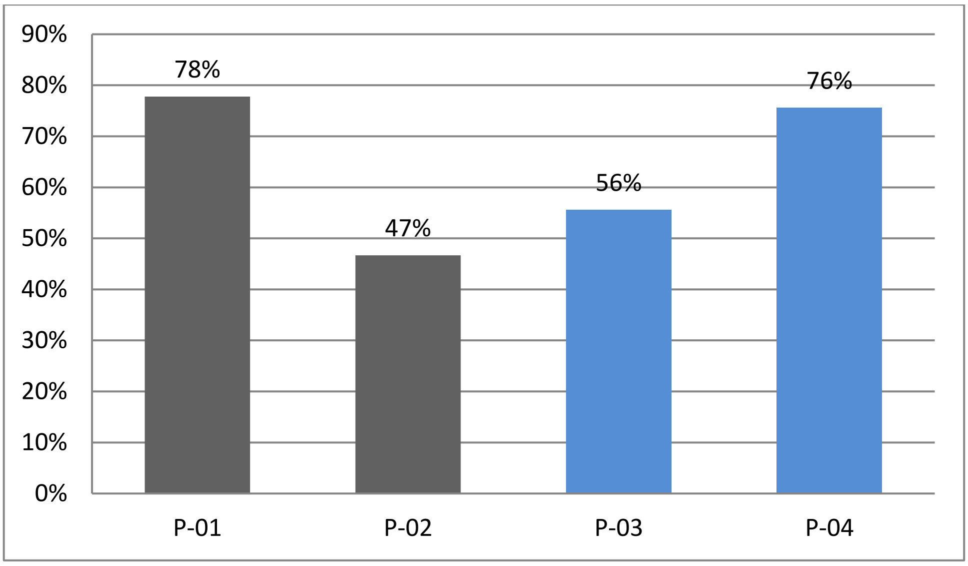

Figure 4. Bar chart with the average of companies for each indicator of the People variable

4.2.3. Analysis of the bar chart based on the Information variable

With the I-01 practice indicator, it is assessed the ease and availability of information accessible to employees about CP, as the results in Figure 5 show. Through interviews and visits to companies, it was found that some companies do not have or make available information on CP, while others provide information related to the sustainability of its process.

Indicator I-02 verifies whether there is information on the financial indicators in order to report progress related to CP, with an average of 47%. It can be inferred that there is little availability of financial indicator information on CP progress, and companies, when presenting such information to employees, share them with management and supervisory people. As pointed out previously, information sharing is important in a context of green supply chain management (Gandhi et al., 2016).

Through performance indicators I-03 and I-05, it is noticed that CP and sustainability information in the companies that have them is not updated frequently. Through the interviews it was identified that the update occurs quarterly. It is important that this information is available in real time in a green supply chain context (Bag et al., 2020).

In general, companies make CP information available in a comprehensive manner, which makes it difficult to identify critical points. Therefore, it would be more interesting if companies adopted detailed data for environmental management, especially in the production sector, where there is greater possibility of improvement actions.

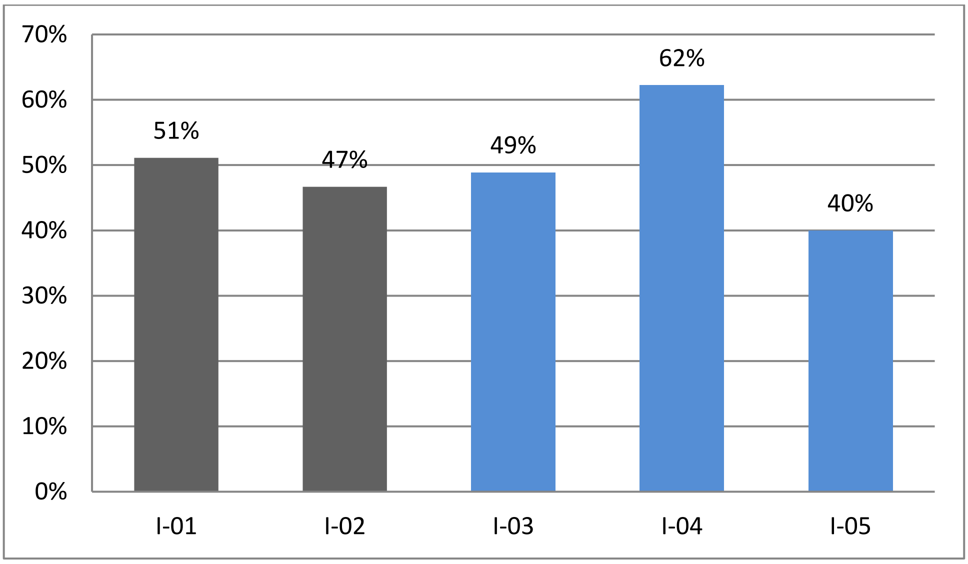

Figure 5. Bar chart with the average of companies for each indicator of the Information variable

4.2.4. Analysis of the bar chart based on the Supplier, Organization and Customer variable

It is noticed through indicators SOC-01 and SOC-02 in Figure 6, that there is some participation of the supplier/customer in the product and process development, besides their participation in revisions not only of new products and processes, but also participation in the improvement of existing ones.

In the first indicator there is a very strong participation of customers in the development of new products and processes, and this is because most of the companies studied manufacture and supply parts to other companies, especially in the automotive sector. The second indicator shows that the participation of suppliers/customers in continuous reviews is not so strong, since the participating companies produce serial parts. The value of SOC-03 indicator is equal to 53%, which shows that the amount of incentives to suppliers and customers to achieve cleaner production is relatively low, and this may be detrimental to effective green supply chain management.

The SOC-04 performance indicator shows that companies care about the processes and products adopted by the supplier/customer, and this is important in a context of green supply chain (Thakker and Rane, 2018). In both cases, external audits are performed to obtain environmental and quality seals. For the SOC-05 indicator, when compared with the other indicators of this variable, and also from the interviews conducted, companies usually adapt their products or processes at the request of customers.

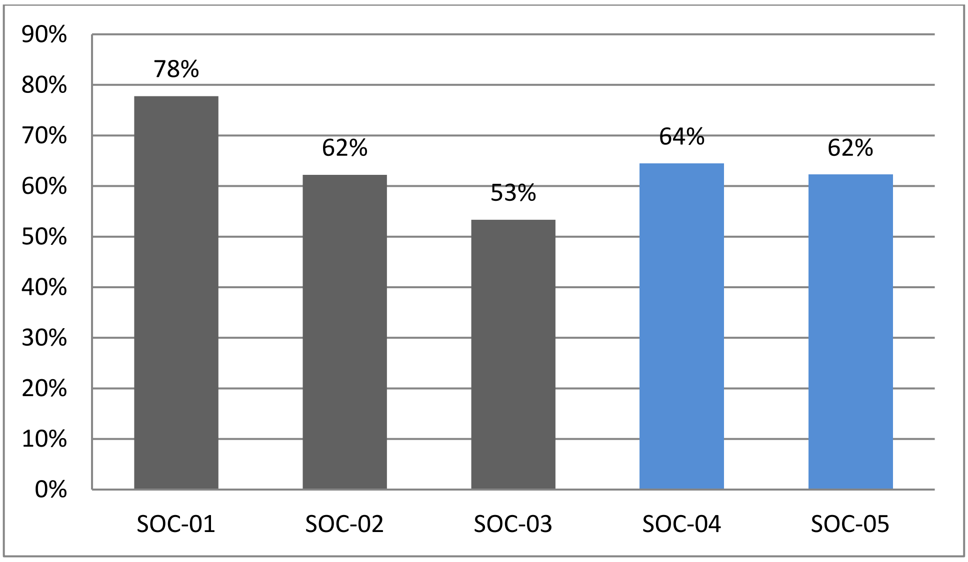

Figure 6. Bar chart with the average of companies for each indicator of the Supplier/Organization and Customer variable

4.2.5. Analysis of the bar chart based on the Environment variable

According to Bag et al. (2020), factors such as solid waste recycling rate and water consumption along the process steps can provide a real picture to management, and firms can gradually move towards a circular economy by focusing on these parameters.

The result of indicator E-01 (Figure 7), which refers to the use of waste incinerator, showed that there are few companies that own or use solid waste incinerator. The incinerator is a great ally for the reduction of solid waste in landfill or dump, and it even eliminates substances that are considered risky. Most of the companies studied justify not using the incinerator because they reuse all the waste generated. However, in its final cycle, it is disposed of in landfill. It should be pointed out that product disposal in landfill or incineration should be avoided, since regulatory restrictions usually discourage companies from doing that (Singh and Agrawal, 2018).

Indicator E-02, which refers to the sustainable use of disposed slag, had the worst average of all indicators presented in this study. When companies dispose the slag from the process, they understand that this is the last step in the cycle of this material (Wei and Huang, 2001). With the visits, it was found that two participating companies are developing a project together with universities to use this disposed slag.

The studied companies are very concerned about the control and monitoring of particulate materials, as can be seen from indicator E-03. However, the presence of equipment that controls the emission of gases is still very low, which can be seen in the value of 47% of indicator E-04.

In the process of sand mould casting, water is used to moisten the sand for making moulds, for cooling equipment, especially furnaces. The result of E-05 indicator shows the concern of the studied companies with the reduction of water usage, and it is verified in some companies that there are rainwater recovery systems and also adequate distribution systems for each process.

Despite good values of E-03 and E-05 practices, companies face difficulties in reducing solid waste and water consumption, keeping the vast majority of their stable use, as shown by the values of performance indicators E-06 and E-07.

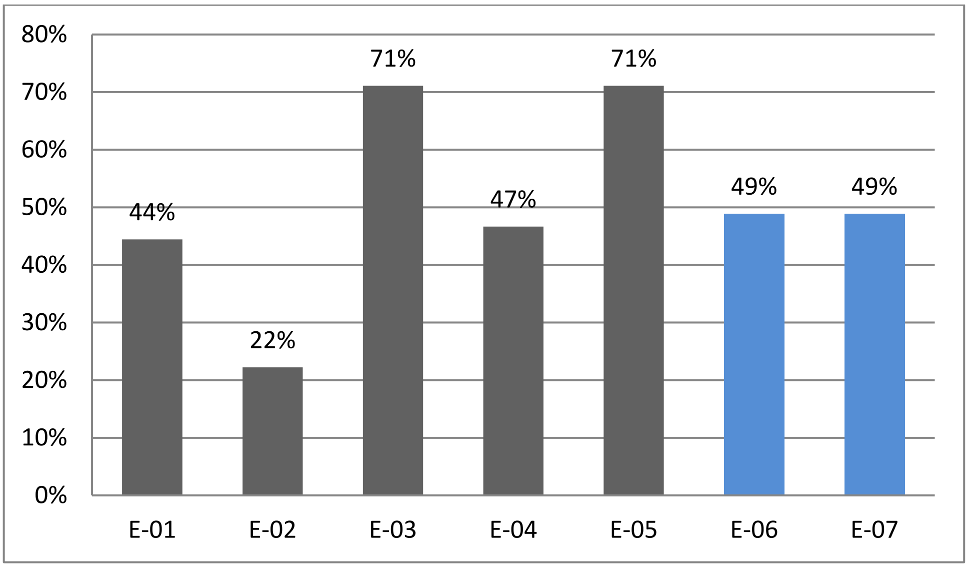

Figure 7. Bar chart with the average of companies for each indicator of the Environment variable

4.2.6. Analysis of the bar chart based on the Product Development variable

Regarding indicator PD-01 in Figure 8, it was found that the practice of product life cycle management is still weak. However, in some companies it was observed that this practice is more focused on processes.

Indicator PD-02 showed that there are practices aimed at product improvement to reduce environmental impact. However, changes made by companies are usually about replacing harmful material with less harmful material, as long as it does not affect product quality and also meets customer demand.

In many of the companies investigated there are studies focused on the development of components so that they can be easily recycled, even in partnership with universities and also in their research and development sectors. Recycling is very important because it inhibits raw material extraction and prevents the disposal of waste in landfills (De Oliveira et al., 2019).

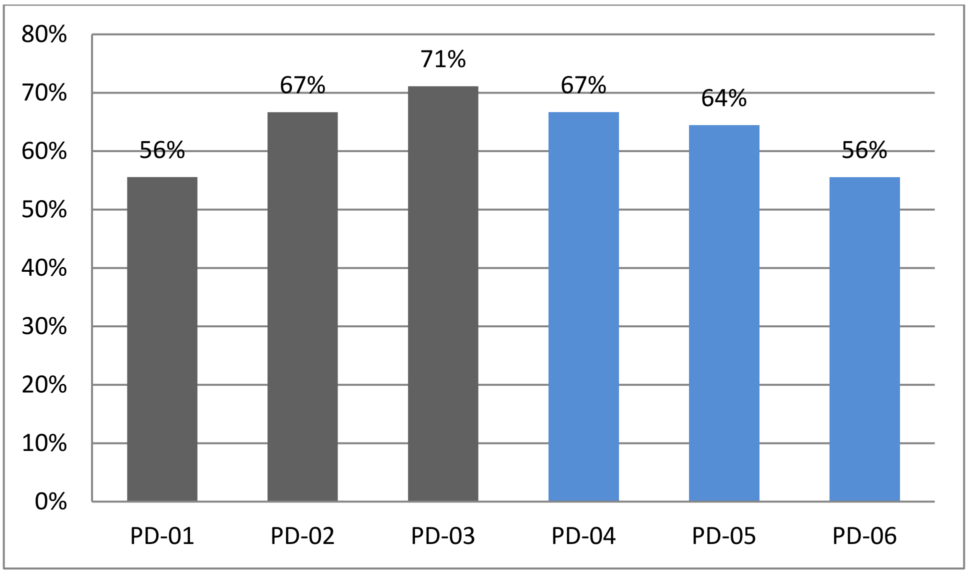

Figure 8. Bar chart with the average of companies for each indicator of the Product Development variable

It was observed in the PD-04 performance indicator that, even with weak and embryonic practices, companies have been showing a reduction of material harmful to the environment. It is worth noting that part of this reduction regarding material replacement is because companies seek to meet environmental and customer requirements. It can also be said that such reduction of harmful material is because companies use recycled material from the process itself, also aiming at cost reduction. Although companies still invest very little in adapting the product for the reuse of recycled material, good results can be verified according to the PD-05 performance indicator.

For the PD-06 performance indicator, the studied companies show some concern with the extension of the product's useful life, with material substitution as the main action for this indicator.

4.2.7. Analysis of the bar chart based on the Process variable

Analysing the result of indicator PR-01 (Figure 9), it is noticed in the value of 82% the significant concern to reuse the sand used in the casting process, since such raw material can be reused several times until when the grain size of the sand is affected, which is crucial for mould quality.

With the visits to the companies studied, it was noticed in some of them that there are sand grain recovery machines. It is a device that performs vibratory crunching through friction with vibratory screening, which ends by peeling the resin and smoothly polishing the grains, without reducing its grain size. For tabulation of results this was considered the best practice.

In the second practice indicator PR-02, it was observed that the companies that make use of lean manufacturing techniques have as main objectives the improvement of performance in production and reduction of waste, putting environmental issues in the background.

With the result of the PR-03 practice indicator, it was observed that companies perform the separation of waste before being recycled or reused, mainly sand, which is incorporated by binders in the moulding process. This practice is widely used due to the high cost of disposing of the material, that is, the reuse of this waste positively impacts the financial aspects of the company, as well as the assessment and control of toxic material, which explains the good result expressed in indicator PR-04.

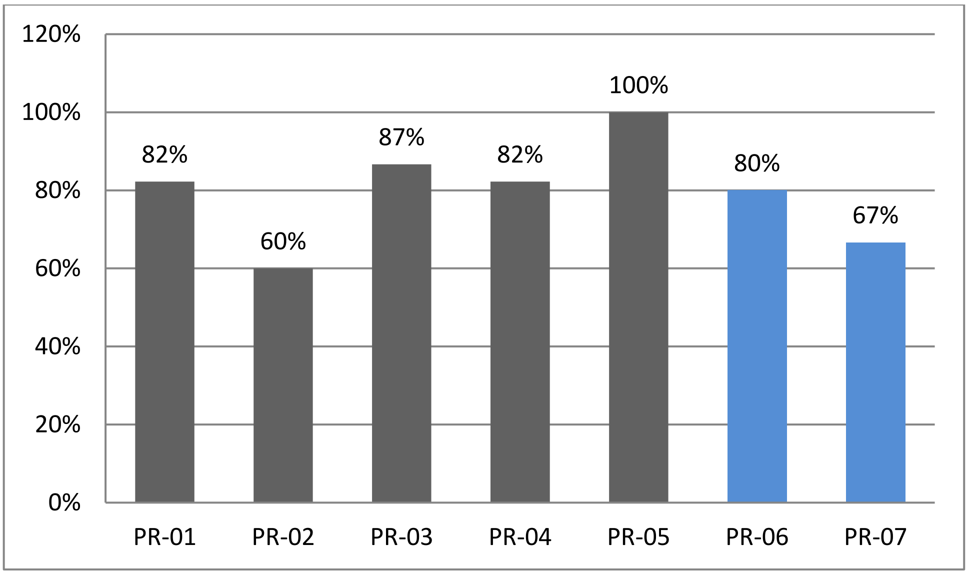

Figure 9. Bar chart with the average of companies for each indicator of the Process variable

The result of the PR-05 practice indicator shows that all companies studied send unused sand to landfills, which is considered by the companies the most appropriate place for disposal of this raw material in its final cycle. With the visits it was observed that only one participating company has its own landfill for disposal, while the other companies send materials and waste from the production process to landfills under the responsibility of third parties.

The companies achieved good results for the PR-06 indicator, which shows that the practices are well structured so that the companies have a good performance. In the performance indicator PR-07, the companies did not obtain a result as good as the previous indicator, and this is due to the fact that all LM actions present in the companies are focused on production, thus there are no indicators that can evaluate the performance of lean manufacturing applied to the company in the environmental context.

4.2.8. Analysis of the bar chart based on the Energy variable

PE-01 practice indicator (Figure 10) shows that the development of new products that contribute to energy consumption is relevant for the studied companies, with an expansion of activities developed by the foundry, largely due to the demand of the automotive sector for parts machining and component casting services. It was also observed that many of the innovations present in the companies studied are incremental, that is, they are improvements of other existing processes.

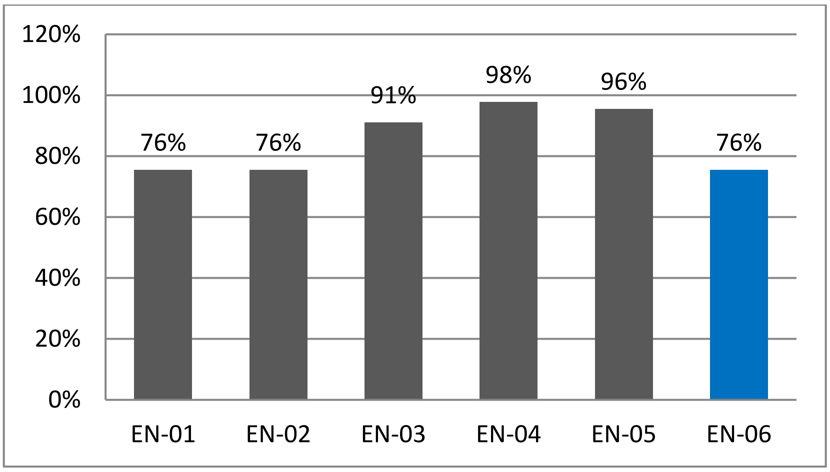

Figure 10. Bar chart with the average of companies for each indicator of the Energy variable

The search for product implementation that requires less energy use has proved to be an important issue faced by companies that seek to develop products and processes for the lowest possible use of inputs, which explains the result obtained by the practice index of indicator EN-02. Some companies also pointed out that the development of these products depends significantly on customers who, in some cases, develop parts and outsource manufacturing.

With regard to the practice indicators EN-03 and EN-04, it was observed that companies perform great control in the use and accounting of energy sources, by means of monitoring expenses and analyses, aiming at eliminating possible waste. Some companies have software for consumption management, in addition to inserting meters for the consumption of gas, fuel oil and electricity.

The main source of energy for casting companies is electricity, and electrical equipment has an operational advantage over others. The result of the practice indicator EN-05 shows that companies adopt various processes aimed at reducing electricity consumption or even replacing the use of electricity with gas.

In general, the main motivation for companies to adopt energy reduction practices is directly related with cost reduction, which depends significantly on the type of innovation used.

4.3. Presence of Lean Manufacturing in sand mould casting companies

In the analysis of the applicability of lean manufacturing in sand mould casting companies aiming at cleaner production, it was found that only one company of the nine studied has production fully linked with LM, as shown in the chart in Figure 11.

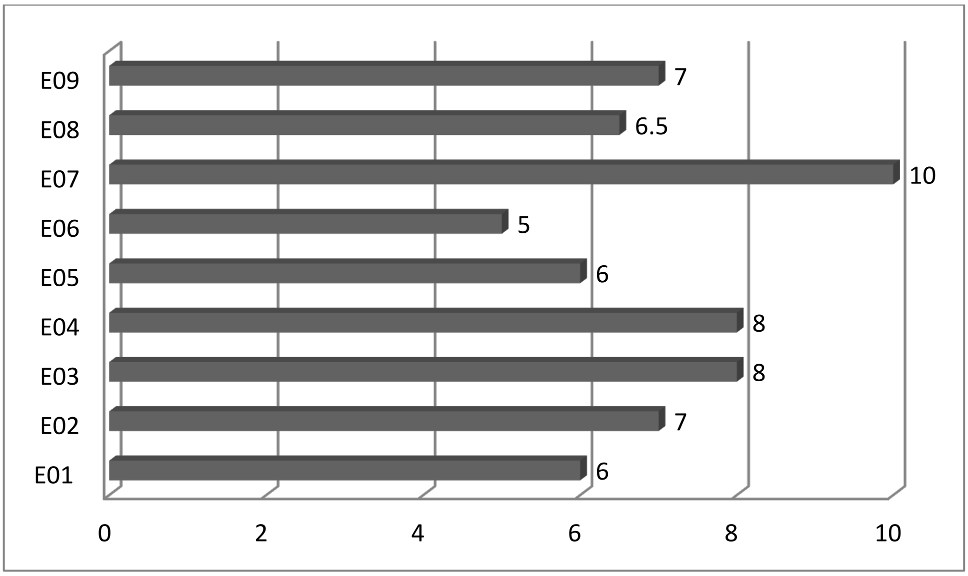

Figure 11. Bar chart with average values of the companies in the LM assessment

It was observed by visiting company E07, which obtained the highest score in this evaluation, that it has its entire plant conceived in the concepts of LM. The study also shows that companies E04 and E05 also perform very strong application of lean manufacturing techniques aiming at achieving CP.

Company E06, which was rated as contender, performed the worst. This is because company E06 is undergoing the implementation of lean manufacturing techniques at its plant in order to achieve better process results, and also with the intention of reducing waste and environmental impact (Verrier et al., 2014).

The result of the lean manufacturing checklist shows that most companies have a significant application of standardized operations that establish precise procedures for the work of each operator in production (Figure 12). It is also observed in Figure 12 that most studied companies consider Quality control (zero defects) as very important in their operations, and it is inferred that they know the economic benefits that can be derived from quality in production (Verrier et al., 2014).

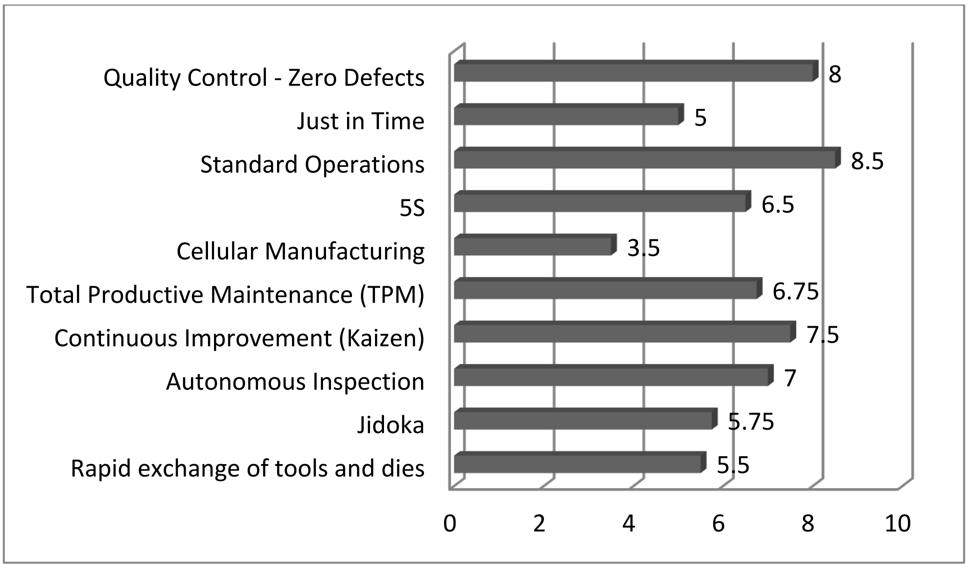

Figure 12. Result of the LM checklist

Cellular manufacturing achieved significantly low results, which may have been caused by casting companies working in a line layout. However, with the visits and interviews, finishing cells in some of the companies studied were observed.

Finally, the application of the other techniques is considered average, indicating that the process of implementation of these techniques in some companies is being consolidated, which ends up preventing an effective result regarding cleaner production.

5. Conclusions

By applying the questionnaire it was identified that companies have concerns related to the environment, and present actions that were considered in this research. However, specific actions related to CP are still scarce in most companies. Among the surveyed companies, the development of new products is linked with the automotive sector, which absorbs a large part of the sales of these companies. This was interpreted as a hindrance to the implementation of some CP actions, especially in product development.

It was found that the environment factor is not yet a priority for companies. However, considering the overall average of the companies studied, it can be inferred that they reached the minimum necessary for the application of CP, and only one company reached low practice and poor performance, requiring special attention. With the average practice result of 66% of all participating companies, it can be inferred that companies have good practices that can be scaled up for better results. It is also observed that in five indicators the average of the results of practice and performance were identical, and in the other indicators there was little difference, which shows the ability of the companies studied to perform adequate actions, requiring improvement in some cases.

In the LM checklist there was a strong application of standardized operations, which is natural for a casting company, in addition to the application of quality control and zero defects, which is very recurrent in companies, since the product is responsible for the company's value. However, it is important to mention that companies do not have LM indicators that are directly linked with CP.

This Benchmarking of Cleaner Production in sand mould casting companies, besides making a diagnosis of eight variables of the companies' production process, guides the companies on which activities they need to develop actions and what results should be achieved.

The improvement of practices and performance of a company regarding cleaner production is considered to be beneficial to supply chain management in the context of sustainability, as the other participating companies are likely to seek ways to reduce environmental impact, and the diagnostics provided by this work may also be used by those companies. In this context, it is suggested as future work assessing whether the practices and performance of CP would effectively be disseminated across the companies in the supply chain.

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